The application of knowledge based engineering to design for Wire+Arc Additive Manufacture (WAAM)

Conference or Workshop Item

The Application of Knowledge Based Engineering to Design for Wire+Arc Additive Manufacture (WAAM)

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Abstract

Wire+Arc Additive Manufacture (WAAM) is well suited to Aerospace applications, due to its ability to produce medium to large structural parts with good structural integrity, and lower manufacturing cost/ waste material than conventional manufacturing processes. However, designers of WAAM parts need expert knowledge of WAAM to maximise the benefits, and substantial modelling effort is required to develop the digital models that are needed for design assessment and manufacturing. This paper introduces Knowledge Based Engineering (KBE) as an approach to automate WAAM design assessment and manufacturing planning for aircraft structural parts. A prototype KBE tool for WAAM has been developed that can check adherence to WAAM design guidelines, perform cost estimations and automatically generate the CAD models that are required for design assessment and manufacturing planning. The paper also includes a case study design assessment for an aircraft structural part.

1. Introduction

Additive Manufacture (AM) refers to the family of manufacturing processes that build up parts layer by layer in an automated process, directly from a 3D CAD model. Wire + Arc Additive Manufacture (WAAM) is an AM technology that uses wire feedstock to produce parts by depositing material layer by layer onto a substrate plate, using welding technology controlled by a robot or CNC machine. For precision applications, the WAAM part is usually deposited as near net shape and machined to achieve the required tolerance and surface finish. Typical deposition rates are up to approximately 1.5 kg per hour and layer height is typically 1 - 2 mm (Williams et al. 2015).

WAAM allows the production of high value structural parts with greatly reduced waste material, lower cost and shorter lead times than conventional manufacturing processes (Addison 2015). This makes WAAM ideally suited to the production of stiffened aircraft structural components such as ribs, spars and frames, which are currently machined from billet or forging with a huge amount of waste material. In the Aerospace industry, the buy-to-fly (BTF) ratio is used to measure the waste material during the manufacturing process and is defined as the ratio of the mass of purchased material to the mass of the finished part that is flown on the aircraft. Allen (2006) states that the buy-to-fly ratios for aero engine components can be as high as 25, highlighting the substantial material saving benefits of a using near net shape process like WAAM.

One of the challenges in using WAAM for industrial applications is the expert knowledge that is required to assess the suitability of a part for WAAM and to determine the best build orientation and build sequence for the WAAM process (Lockett et al (2017). Furthermore, cost estimation is often necessary to justify the use of this new manufacturing process by comparing the WAAM cost with conventional manufacturing processes such as machining (Martina and Williams, 2015).

The objective of the KBE application presented in this paper is to ease the design assessment process for WAAM and reduce the amount of expert knowledge that is required by the designer. The KBE tool will automate the labour intensive aspects of the design for manufacture process for WAAM, including design assessment, manufacturing planning and cost estimation. Section 2 of the paper provides a literature review and Section 3 describes the main steps of the WAAM design assessment process. In section 4 the knowledge capture for the design assessment tool is presented and Section 5 introduces the KBE tool implementation. Finally in Section 6 a case study is presented, then conclusions drawn.

2. Literature Review

Knowledge Based Engineering (KBE) is defined by Cooper, Fan and Li (1999) as 'a particular type of knowledge-based system that is based upon an object-oriented programming language and is tightly integrated with a geometric modelling tool'. Corallo et al. (2009) describe KBE as a software-based technique that enables the capture and storage of tacit knowledge inside an organization and the re-use of that knowledge in the form of automated or semi-automated applications. KBE can capture product and process multidisciplinary knowledge by means of integrated software applications. These can then automate the repetitive design activities, thereby reducing engineering design time and cost (La Rocca and van Tooren 2010). A key element of KBE tools is the use of generative design models that can automatically create or modify CAD models using embedded knowledge.

In the last twenty years KBE has been applied for a range of applications to support complex design tasks in aerospace, automotive, ship building, architectural and other areas. KBE was first popularised in the 1990s with the introduction of commercial tools like ICAD (originally from ICAD Inc.) which used a declarative language to program generative CAD models with encoded design knowledge. More recently CATIA from Dassault Systemes has added KBE capabilities to a conventional CAD package through the use of macro programing functions and APIs.

KBE can substantially reduce engineering design time and streamline the product development process, providing provide major benefits to a business. It can help automate tedious and time-consuming parts of design, and free up engineering resource for more value added aspects of the design process. It can also help ensure consistency, reduce variation and help ensure new designs created meet specified constraints such as cost, legislation or manufacturing capabilities (Cooper, Fan, and Li 1999). Most KBE systems aim to separate the automation aspects from the knowledge management, to allow the knowledge to be updated without needing to modify the core modelling application.

A number of methodologies have been proposed to support the development of KBE applications. MOKA (Methodology and tools Oriented to Knowledge-based engineering Applications) (Stokes, 2001) is the best known, and identifies the steps required to develop a KBE application:

- identify needs,
- justify scope and assess risks,
- capture and structure the raw knowledge,
- formalise knowledge to develop product and process models,
- package the application,
- distribute, introduce and use.

More recently the KNOMAD methodology (Knowledge capture, Normalisation, Organisations, Modelling, Analysis and Delivery) has been developed which focusses specifically on integrating KBE within a multi-disciplinary design optimisation environment (Curran, Verhagen and van Tooren, 2010).

KBE has been explored for aerospace applications both through academic research and industrial applications. Choi (2007) developed a knowledge-based engineering system for estimating manufacturing cost and weight of a composite structure using CATIA v5.The tool uses a simplified representation of the structure created using CATIA and automatically creates a finite element model of the structure that is used to optimise the component thicknesses in the structure. La Rocca and van Tooren (2010) developed a KBE tool to act as a multi-model generator (MMG) for a multi-disciplinary design optimisation (MDO) tool for aircraft design. The MMG is a parametric design environment for novel aircraft configurations and a model generator to automatically generate the different geometry models that are required for different design analyses in the MDO process. Quintana-Amate et al. (2017) developed a KBE tool to predict manufacturing cycle times for carbon fibre reinforced plastics (CFRP) wing parts. They encoded design for manufacture knowledge into the KBE application and used machine learning to predict manufacturing time from a database of existing wing designs.

The KBE tool presented in this paper aims has been developed following the general approach of the MOKA methodology, starting by identifying the scope of the tool, then capturing and formalising the knowledge into a KBE application.

3. Overview of WAAM design to manufacture process

The first step in KBE tool development is to identify the KBE tool needs. This section summarises the steps involved in the design assessment process for a WAAM part, and identifies the aspects that will be included within the tool.

The WAAM design to manufacture process starts with a CAD model of a designed part as its input (Figure 1 (a)). The part design is first checked against a set of WAAM design rules and design changes may be recommended if any design guidelines are not met. The CAD model is then modified to create the WAAM ‘preform’, which is the model that will be used to plan the WAAM deposition. The preform includes a material allowance for post-machining (i.e. increased wall thickness and height to allow for material removal during machining), and adjustments to design features that are not compatible with WAAM (for example removing small holes or extending small features for deposition). Once the preform CAD model has been created, the substrate must be designed and added to the model. The substrate is the plate that will be used as the base for WAAM deposition

(Figure 1 (b)) and includes a periphery excess to allow for work holding during deposition and machining. The designer decides the most appropriate position and orientation for the substrate based on expert knowledge of the WAAM process. The preform CAD model is then divided into the region to be deposited (Figure 1 (c)) and the region that will be formed from the substrate (Figure 1 (d). The volumes that are required for cost estimation must then be calculated from the CAD models of the final part, preform, deposited region and substrate. Finally a cost estimation is performed for the WAAM manufacture. Often it is desirable to also perform a cost estimation for conventional manufacture using machining to allow for comparison. The CAD model of the preform can then be used to create the toolpaths for the WAAM deposition and post-machining. Figure 1 (e) shows the 'as-deposited' part and Figure 1 (f) shows the final part after post machining.

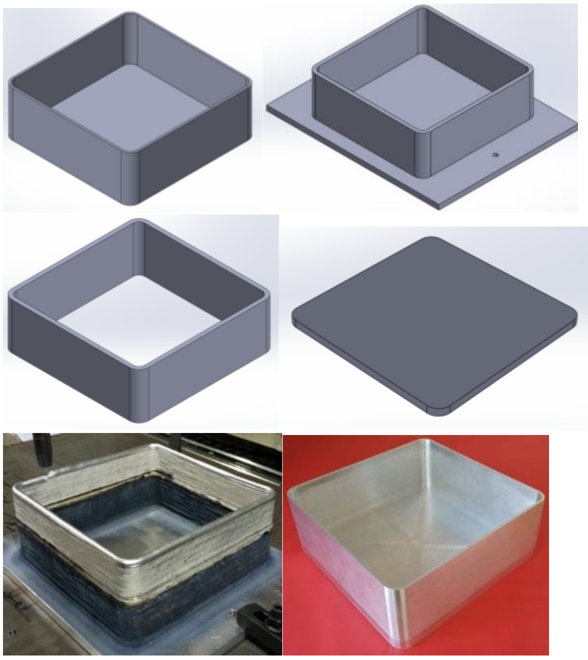


Figure 1. Example WAAM part showing (a) part model, (b) preform model, (c) deposition model (d) flyaway substrate model (e) as-deposited part and (f) finished part.

The choice of substrate position and build orientation can have a substantial impact on the BTF ratio and on the final part cost, so it is often useful to perform a cost estimation on several build options before making a final decision on the WAAM build.

The KBE application presented in this paper focusses on the WAAM design assessment and cost estimation process. Path planning is not considered within this application.

4. Knowledge Capture

The knowledge capture phase formalises the knowledge that will be encoded into the tool and is a key part of the development of any KBE tool. Knowledge engineering classifies knowledge into explicit knowledge (design manuals, engineering method) and tacit knowledge (rules of thumb, heuristics, and observations). This KBE tool incorporates three main areas of knowledge - design guidelines, geometry modelling and cost estimation. The knowledge capture was undertaken by working with WAAM experts in the Welding Engineering and Laser Processing Laboratory at Cranfield University (Lin, 2015 and Emms (2016). The main outputs of the knowledge capture are summarised in the following sections.

4.1 Design Assessment

A set of WAAM design rules have been developed by Lin (2015), Emms (2016) and Lockett et al. (2017), based on interviews with WAAM subject experts at Cranfield University. A subset of the design rules have been formalised into the KBE tool to assess the suitability of the design for WAAM. The design rules assessed in the KBE tool are:

- Minimum part size
- Maximum part size
- Maximum substrate size
- Maximum plate thickness for billet
- Minimum WAAM radius size
- Minimum WAAM feature size
- Minimum WAAM hole size
- Minimum WAAM wall thickness
- Minimum CNC wall thickness
- Minimum WAAM wall angle
- Minimum CNC Radius size
- Minimum web thickness
- Maximum pocket depth
- Symmetry factor

4.2 Modelling

A key feature of the KBE tool is to automatically generate all of the CAD models that are required for BTF ratio calculation, cost estimation and path planning. Interviews with WAAM experts showed that a substantial amount of time is spent modifying CAD models and extracting geometric information from the CAD models. These activities can be automated using the generative design capabilities of KBE. The knowledge capture process identified five CAD model variants that are required in the WAAM design assessment process and are created automatically by the tool:

- Part Design
- Preform with machining allowance and removal/ modification of small features

- Purchased substrate
- Flyaway substrate (the region of the substrate that will remain in the final part)
- Material to be deposited
- Equivalent billet for machined version of part

4.3 Cost Estimation

The cost model in the KBE tool uses the cost modelling approach presented by Martina and Williams (2015) to compare WAAM and machining costs. The cost model considers fixed costs (costs that do not change based on the volume of parts produced), variable costs (i.e. costs that vary based on the volume of part produced), material costs, material deposition rates for WAAM, material removal rates for machining and part volumes. The cost estimation does not include inspection costs, surface treatments, assembly operations or non-recurring engineering costs.

The cost estimation process requires two sets of inputs – firstly the volumes that are generated from the WAAM models in the design assessment process as detailed above, and secondly the parameter values for the manufacturing processes and materials. The main input parameters to the cost model are the WAAM fixed costs, WAAM variable costs, CNC machining fixed costs, CNC variable costs and material costs.

The outputs generated by the cost estimation are BTF ratios for WAAM and CNC production, and cost estimates for WAAM and CNC machined parts including non-recurring costs for different batch sizes.

4.4 KBE tool process flow

A process flow for the KBE tool was developed based on the design assessment process described previously and is shown in Figure 2.

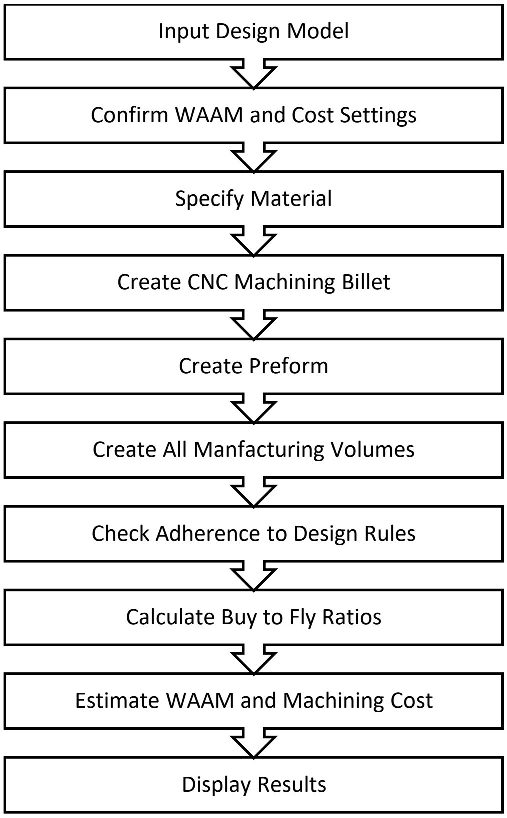


Figure 2. KBE process flow for WAAM assessment tools

5. Implementation of Demonstrator KBE Tool

The knowledge formalisation phase of KBE development translates the captured knowledge into product and process models that can be packaged together to form the KBE tool. The overall architecture for the KBE tool is shown in Figure 3. As shown in the figure, the main inputs to the KBE tool are the CAD model of the part to be manufactured and the input settings for WAAM deposition and the cost estimation. The KBE tool then assesses the design against the design guidelines, generates the required CAD models and performs the cost estimation. Materials and cost information are stored in external files so that they can be maintained separately from the main software tool. The outputs of the system are the design assessment results, CAD models for manufacturing planning, BTF, design cost estimation and manufacturing time estimation.

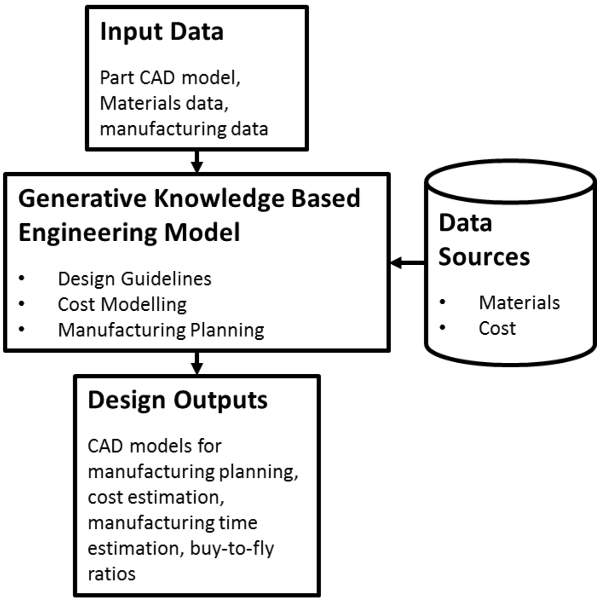


Figure 3. KBE Tool process Flow

The demonstrator WAAM design assessment KBE tool has been developed using CATIA v5 VBA script. Feature recognition has been used to automatically recognise some feature types to allow for automatic design assessment. In order to achieve this, the CAD model of the design must be created using the feature based design tools in CATIA v5. For example using the shell and stiffener features to create the part walls, and pocket and hole features must be used for other cut-out features. Feature recognition was also implemented to identify webs as a special case of wall feature. The modelling and cost estimation can be performed on any CAD solid model without the need for feature based modelling.

6. Software Operation

The KBE tool runs as a macro in CATIA v5. The main input screen is shown in Figure 4. The KBE user interface is shown in a window alongside the main CAD interface.

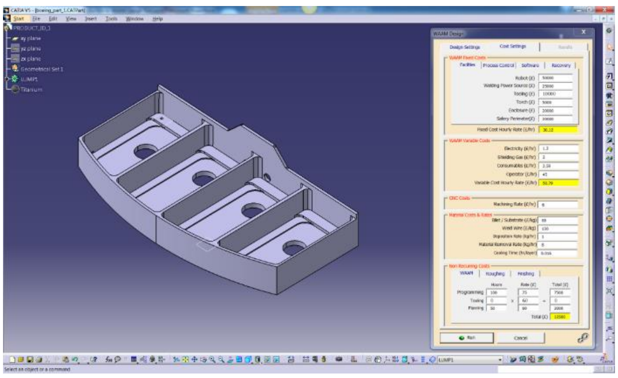


Figure 4. KBE user interface in CATIA v5

The user interacts with the KBE system through the main user interface screen shown in Figure 5. In this window the user selects the part to be analysed and position of the substrate. The user also inputs parameters for the substrate thickness, substrate size and shape, and WAAM deposition parameters. The material properties of the part are read directly from the CATIA model.

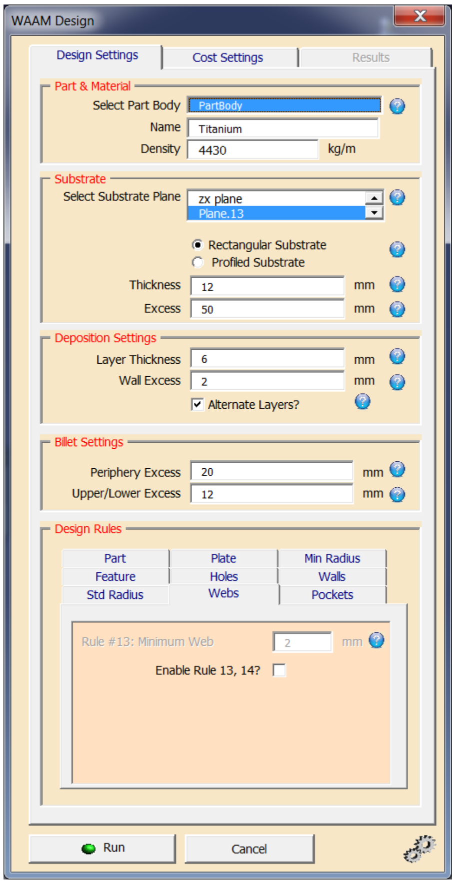


Figure 5. Main user interface for KBE tool

The model is run by clicking on the 'Run' button. The tool then performs the design assessment, generates the CAD models and runs the cost estimation. Figure 6 shows examples of the CAD model outputs that are generated by the system

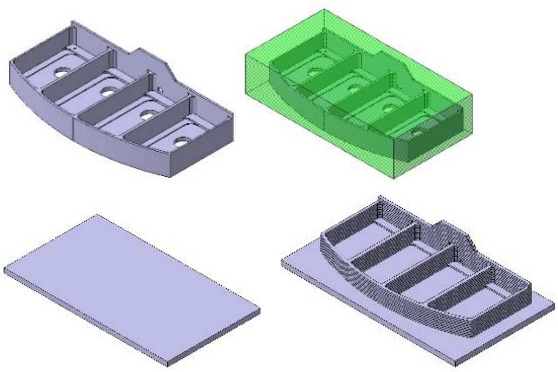
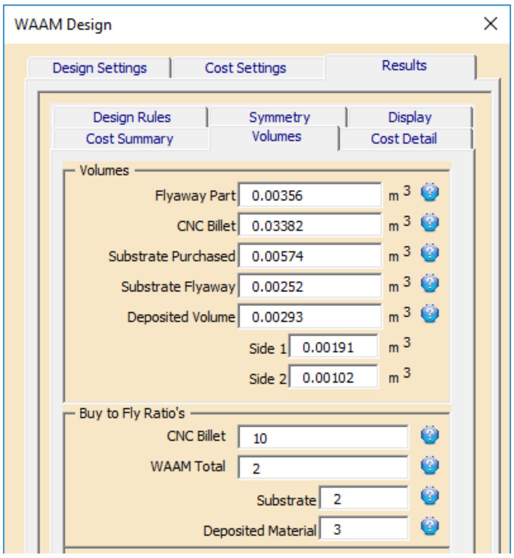
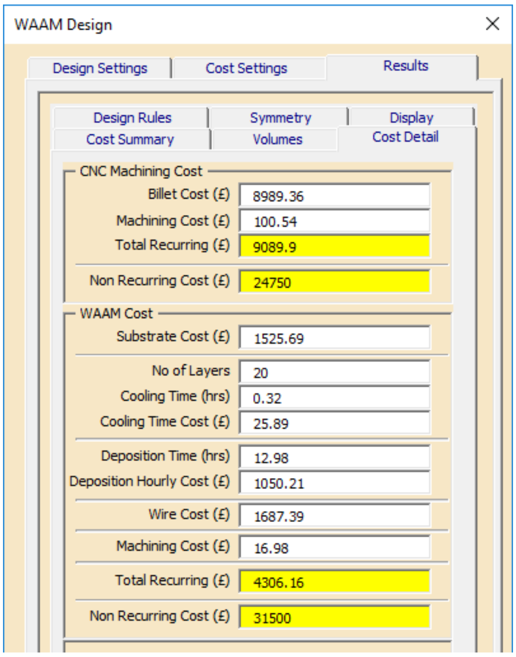


Figure 6. Models by KBE tool (a) designed part, (b) billet for machining (c) substrate (d) preform for WAAM deposition including substrate

The BTF ratio results and cost estimation are then displayed in the results screens. The part is then checked against the WAAM design rules and results are presented to the user as shown in Figures 7.



(a)



(b)

Figure 7 Example results (a) BTF ratio and (b) cost estimation.

7. Case Study

The case study part is based on a machined aluminium frame similar to those found in many aircraft structures. The frame contains multiple pockets giving varying web thicknesses across the part. It has complex surfaces on the upper and lower surfaces to provide a surface landing for external parts. The frame is to be manufactured using aluminium alloy 7050 and is 760 mm long with a mass of 5.8 kg. It is proposed to produce the part using WAAM deposited on a 12 mm thick substrate with a 50 mm periphery excess for work holding. A design assessment of the part has be performed using the KBE tool and the part design and other KBE generated models are shown in Figure 8. The time taken to run the design assessment including cost estimation on a standard PC was 11m and 6s compared to the time taken for manual modelling cost estimation of several hours. The run time can be reduced to less than 2 minutes if the two most time consuming design rules assessment steps are removed.

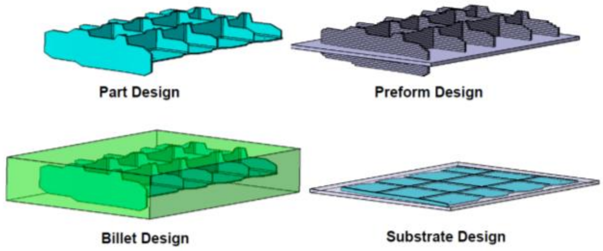


Figure 8. Frame case study part and KBE generated models.

The results of the design assessment are shown in Figure 9, where it can be seen that all the design rules have been met, except that one wall in the part does not meet the minimum stiffener size and another does not meet the minimum wall angle. The first design issue would require a design change and the second is caused by an error in the feature recognition for this part. The results show that the BTF for the part using CNC machining is 39, whereas for the WAAM part is 4 (made up of a BTF of 5 for the substrate and 2 for the WAAM deposition). The waste material for the machined part is 221 kg, compared to the waste material for the WAAM part of 23.2 kg. The symmetry of the WAAM deposition above and below the substrate is also assessed, as shown in Figure 10, and shows that the deposition on the upper side is 89% compared to 11% on the lower side. It can be beneficial to build WAAM parts with symmetrical deposition above and below the substrate to balance the residual stresses caused by the deposition process. This build orientation is therefore not ideal from a symmetry perspective.

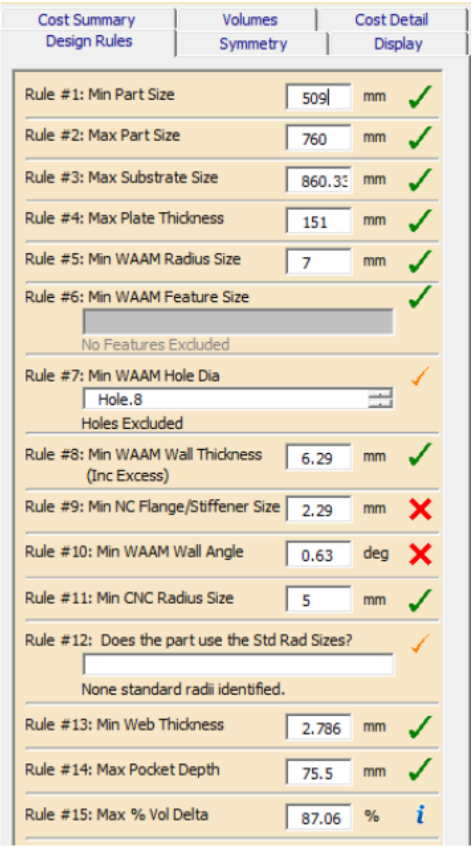


Figure 9. Design assessment for Rib component.

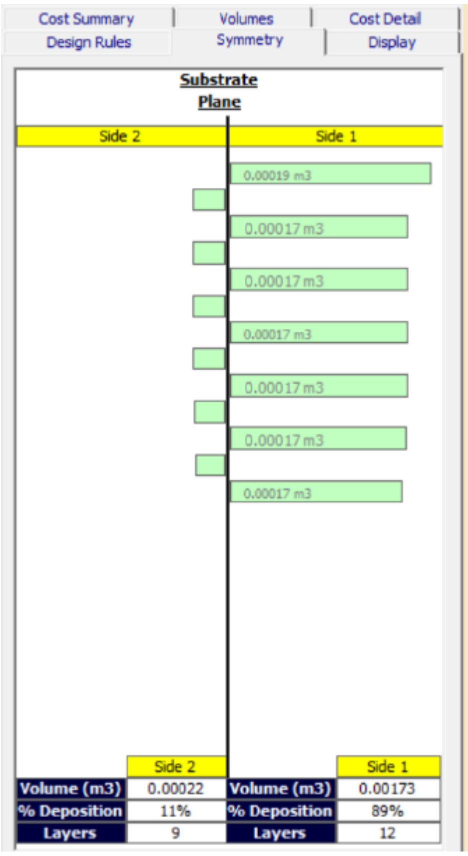
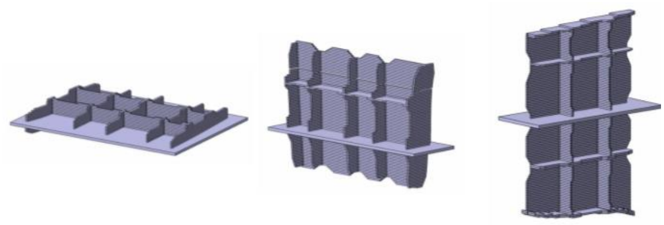


Figure 10. Illustration of part symmetry about substrate

Finally the cost estimation for WAAM and CNC production were performed. The WAAM recurring cost was £850 compared to £1409 for the CNC. This represents a 40% saving by using the WAAM process. Material costs for the WAAM process were £397 vs £1389 for CNC. This was a 70% saving by using the WAAM process. Material costs for the CNC method contributed to 98.5% of the cost.

The KBE tool was also used to compare the cost of three different build orientations for the frame as shown in Figure 10.



A B C

Figure 10. Alternative build options for the aircraft frame.

The results for the three build options are summarised in Table 1. It can be seen in the table that option A gives the lowest cost but the highest BTF and has the least symmetrical depostion. Option C is the most symmetrical but has more than double the cost of option A. For a higher cost material such as Titanium, option C may be a more desirable solution for rate production.

Table 1. Comparison of WAAM build options for aircraft frame

	A	B	C
Overall BTF	4	3	3
WAAM cost	£850	£1676	£1837
Material Distribution	89%/11%	71%/29%	41%/59%

8. Discussion and Conclusions

This paper has described a demonstrator KBE tool for WAAM design assessment. The main features of the tool are the automated assessment of a design against the design rules for WAAM manufacture and a cost estimation tool that allows different build options to be rapidly compared. The tool also generates all of the CAD model variants that are required for path planning and design assessment.

The KBE design assessment tool greatly reduces the time taken to perform design assessment tasks compared to using interactive CAD and cost estimation tools. It also reduces the need for expert knowledge at the design assessment stage and can increase confidence for an organisation considering investing in WAAM technology.

Future work could extend this tool to automate more aspects of manufacturing planning and deposition path generation. Further work on the feature recognition aspects could also increase the tool's flexibility and reduce the processing time.

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